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Comparison of wear debris generated from ultra high molecular weight polyethylene in vivo and in artificial joint simulator

Liu Hongtao [a,*], Ge Shirong [b], Cao Shoufan [a], Wang Shibo [b]

[a] School of Materials Science and Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China
[b] Mechanistic College, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China

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ABSTRACT

The artificial joint simulator is designed to simulate the complicated movement and environment of the artificial joint in vivo. Although the wear loss of materials evaluated on the artificial joint simulator under ISO standard is found to conform to that in vivo, there is a significant difference in the morphology of the wear debris obtained from the tester and human body. It is well known that the wear debris plays an important role in aseptic loosening of the artificial joint, and its morphology indicates the working conditions of the artificial joint. Therefore, it is necessary to distinguish the two kinds of wear debris. In this paper, the comparative study of ultra high molecular weight polyethylene (UHMWPE) wear debris from the implanted artificial joint and hip joint tester was performed on their size distribution, shape, 3-D feature, and thickness. Results show that the wear debris from joint simulator have different sizes and shapes such as strip, block, plate, and spherical etc., their average diameter is 7.54 μm, and its medium diameter is 6.89 μm. The most wear debris from artificial joint have the spherical or subsphaeroidal shapes, and a small amount of the debris have the unbroken plate structure, the average diameter is 1.33 μm, is about 18% of the wear debris' from joint simulator, and the medium diameter of 2.95 μm, is about 43% of the wear debris' from joint simulator. The results are expected to provide both experimental and theoretical foundation for improving the artificial joint simulator and optimizing the evaluation standards of the artificial joint materials.

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1. Introduction

Aseptic loosening is one of the major failure modes of artificial joint. The key reason is that the wear debris of the artificial joint will induce macrophage to secrete osteolytic factor which leads to osteolysis [1–4]. The creation, circulation and phagocytosis of UHMWPE wear debris in vivo takes place in a closed biological system [5–7], which cannot be tested and observed directly. Consequently, it is essential to carry out the simulating wear test of the artificial joint according to ISO standard. However, due to the complicated movement process and wear mechanism of the joint friction pair, it is impossible to simulate the wear behavior of the artificial joint in vivo fully. For example, the wear debris from the artificial joint tester present a different morphology with that from human body, although the wear loss of materials evaluated by the tester conforms to their wear loss under actual conditions. Since the morphology of wear debris can indicate the wear conditions of joint [8–11], it should be an important factor to evaluate artificial joint materials. Unfortunately the current ISO testing standard of artificial joint cannot show the important role of wear debris of artificial joint. In the paper, the size distribution, shape, 3-D feature, and thickness of UHMWPE wear debris from implanted artificial joint and hip joint tester were investigated and compared. This systematic studies help to improve the artificial joint simulators and optimize the standard of evaluating artificial joint materials.

2. Sample preparation

2.1. Wear debris preparation

The UHMWPE wear debris is prepared in vitro by a total hip-joint simulator, following the ISO standard [12]. The wear tests described in this paper were terminated at 1,000,000 cycles, the approximate times of human acting in one year. With the aid of articular endoscope, the joint synovial fluid of three patients whose hips had been replaced for about one year was extracted to collect wear debris of the implanted artificial joint. Both of the friction pairs above are UHMWPE to CoCrMo alloy.

2.2. Separation of UHMWPE wear debris

The 25% calf serum solution is used as the lubricant in vitro wear test of the artificial joint. The serum is made by removing fibrin from plasma, and contains plasma proteins, polypeptide, adipose,

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* Corresponding author. Tel.: +86 516 83591916; fax: +86 516 83591916.
E-mail address: liuht100@126.com (L. Hongtao).

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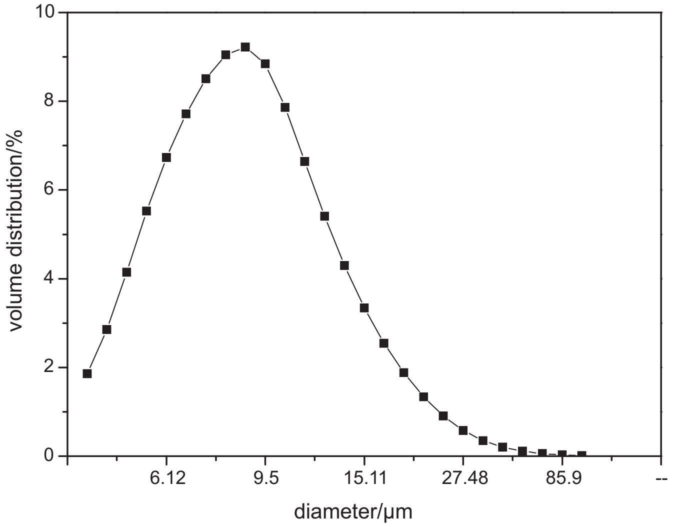

Fig. 1. Size distribution of UHMWPE wear debris from the artificial joint simulating test.

carbohydrate, growth factors, hormones, and inorganic, etc. In order to eliminate the effects of serum on the analysis of the morphology of wear debris, it is necessary to separate the wear debris of UHMWPE from serum in bio-lubricant and collect it. The separating method of the UHMWPE wear debris from joint simulator is described in the following. Firstly, the lubricant containing wear debris was digested by 5 M potassium hydroxide under 60 °C for 48 h, which results in a saponification reaction and the production of free alcohol and some acid salts. During the digestion, the ultrasonic cleaner was used as the pulsator to speed up the reaction. The esters were removed through the digestion treatment. Then, the solution was extracted for 24 h at 27 °C by adding an equal volume of the chloroform/methanol mixture (2:1 in volume). The proteins were removed by centrifugation at 500 rpm for 10 min. This extraction/centrifugation process must be repeated at least three times. Finally, the residual proteins were precipitated with ice-cold ethanol (97%, v/v), followed by centrifugation at 1500 rpm for 60 min under 4 °C. The UHMWPE wear debris was obtained after torrefaction.

The joint synovial fluid mainly consists of hyaluronic acid, its salts, fat, and some proteins, like the calf serum solution, so the separating method of the UHMWPE wear debris from joint simulator is same as above.

2.3. Size and morphology observation of wear debris

The size of wear debris is tested by a Fully Automatic Laser Particle Size Analyzer, and its morphology is investigated using SEM, TEM and MiaoXAM2.5X-50X ultra-precision 3-D profiler.

3. Results and discussion

3.1. Size distribution of wear debris

3.1.1. Size distribution of UHMWPE wear debris in simulating test

Fig. 1 shows the distribution of UHMWPE wear debris obtained from the CoCrMo–UHMWPE artificial joint after 1,000,000 cycles on the total hip simulator. It shows that the range of the diameter distribution of UHMWPE wear debris is considerable wide and small wear debris is in large quantity. The diameter of about 98% of wear debris is 4–20 μm. The wear debris with a diameter over 50 μm take up less than 0.1% of the total debris, and the wear debris with a diameter over 200 μm is hardly found. The average diameter of wear debris is 7.54 μm, and its medium diameter is 6.89 μm.

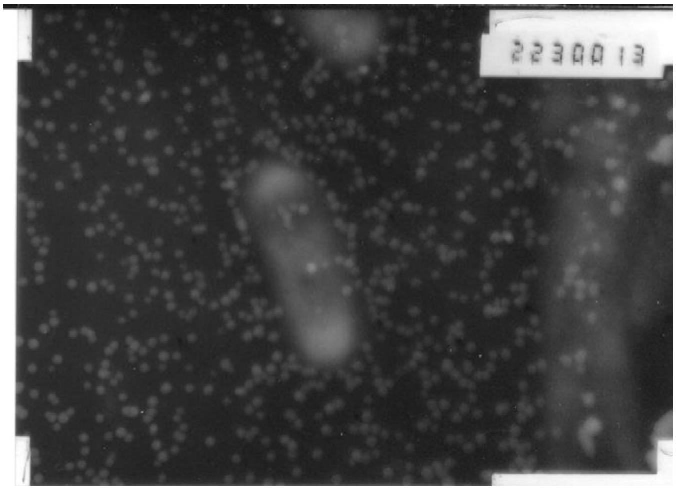

Fig. 2. TEM image (×65k) of wear debris gotten by low-rate quantificational filter paper (3 μm).

Besides micron-sized wear debris, a great quantity of small wear debris with the diameter of 100 nm is also observed using TEM (shown in Fig. 2) when the solution of wear debris is filtered by low-rate quantificational filter paper (3 μm). Therefore, the wear debris produced in the frictional tester has a wide range of diameter distribution, with the measurable range between 100 nm and 200 μm.

3.1.2. Size distribution of wear debris from the implanted artificial joint

Fig. 3 shows the size of wear debris from the implanted artificial joint. Compared to the wear debris generated by the hip joint tester, the wear debris from the implanted artificial joint presents a smaller size. Its size distribution ranges from 0.117 μm to 53.26 μm. They mostly center between 0.5 μm and 5 μm, with the average diameter of wear debris is 1.33 μm, is about 18% of the wear debris' from joint simulator, and the medium diameter of 2.95 μm, is about 43% of the wear debris' from joint simulator.

3.1.3. Comparison between the size of the two kinds of wear debris

The above results indicate that the wear debris produced by the hip joint simulator has a larger average size and wider distribution range. When we walk or run, the force acted on the implanted arti-

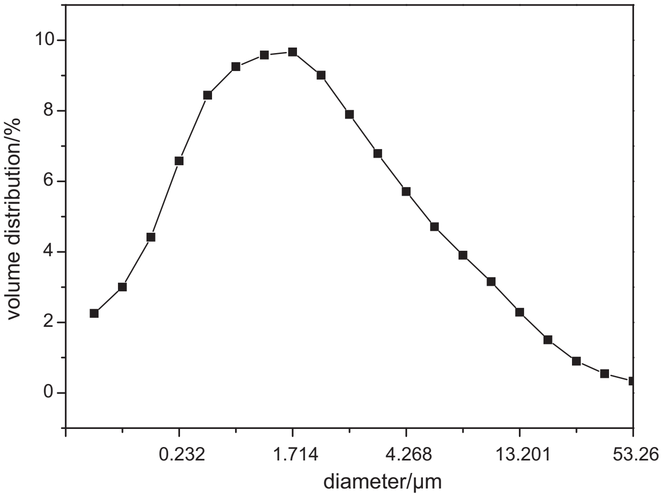

Fig. 3. Size distribution of wear debris from the implanted artificial joint.

ficial joint will be shared by the peripheral muscles of joint. As a result, the transition and change of force are smooth and regular, thus producing the wear debris with a smaller diameter. However, for the hip simulator, the artificial joint takes all the force loaded during test, so when the same outside force was put on the artificial joint and the hip joint simulator, the pressure between friction pairs is different, leading to different wear results.

3.2. Morphology of wear debris

3.2.1. Morphology of UHMWPE wear debris in simulating test

The UHMWPE wear debris of artificial joint in the simulating test shows a variety of morphologies due to the complicated movements of artificial joint. Fig. 4 shows the SEM micrograph of UHMWPE wear debris. It can be observed that the wear debris have different sizes and shapes such as strip, block, plate, and spherical etc. Though the shape of wear debris is complicated, it still can find that the size of wear debris is more larger and the shape is more complicated. When the wear debris is small enough, its shape tends to be spherical or near-spherical.

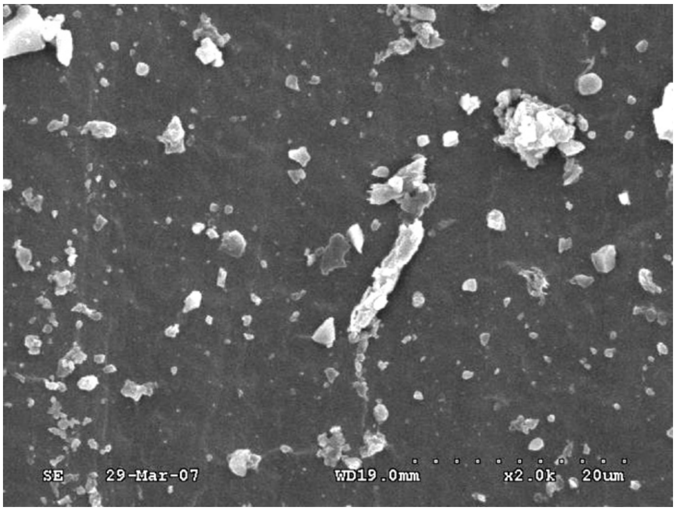

Fig. 4. SEM micrograph of UHMWPE wear debris.

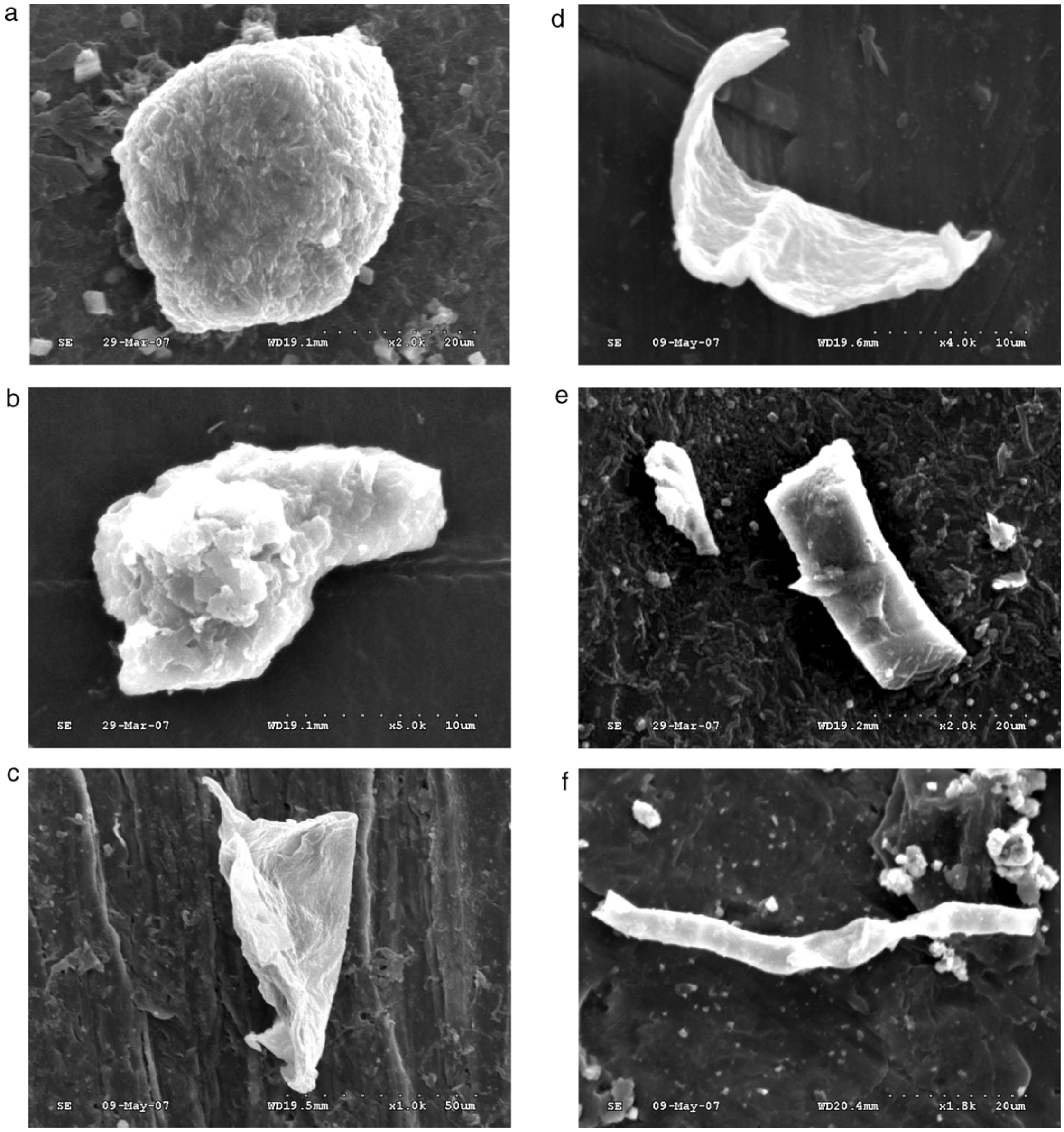
a
SE 29-Mar-07 WD19.1mm x2.0k 20um
b
SE 29-Mar-07 WD19.1mm x5.0k 10um
c
SE 09-May-07 WD19.5mm x1.0k 50um
d
SE 09-May-07 WD19.6mm x4.0k 10um
e
SE 29-Mar-07 WD19.2mm x2.0k 20um
f
SE 09-May-07 WD20.4mm x1.8k 20um

Fig. 5. Typical morphologies of UHMWPE wear debris.

Fig. 5 shows the typical morphologies of wear debris. Research indicates that the spherical wear debris (Fig. 5a) has a diameter of basically less than 50 μm, with wide size distribution and quantity. The larger particles are mainly produced in the process of adhesive wear which greatly depend on the properties of the friction materials [13]. On the other hand, the smaller particles are usually formed by the fragmentation of large wear debris or the exfoliation of surface micro-convex-bodies of friction pairs, related to the rough movement of friction pairs.

Block wear debris has a smaller ratio of length to width, spindle or flat block shape, and complicated shape and texture on the surface (Fig. 5b). Spindle-shaped wear debris is mainly formed in the process of adhesive wear [13]. Their size range is from about 1 μm to 50 μm, and the majority is centered around 20 μm. The wear debris with flat block shape comes from the cracked surface because of the fatigue stress and the separating from wear surface at the weak points by adhesive force. The size of this kind of wear debris is generally above 10 μm, and the size distribution ranges from 10 μm to 150 μm.

Tearing wear debris is the product of composite motion of friction pairs, and is the most irregular in all UHMWPE wear debris (Fig. 5c). This kind of wear debris has irregular shape, rough surface, and good third dimension. The size of wear debris ranges from about 10 μm to 150 μm. This kind of wear debris produced and grew following the direction of movements of friction pairs, and peeling off from wear surface gradually. For different materials and operation conditions, wear debris has different sizes and a wide diameter distribution.

Sheet wear debris is a typical fatigue wear debris and it has a thin thickness and a large plane size (Fig. 5d). The size of this kind of wear debris is from about 20 μm to 100 μm. It can be easily broken into smaller wear debris by external forces.

Rod wear debris has a irregular shape, rough surface and strong dimensional structure (Fig. 5e). The size of wear debris ranges from 10 μm to 100 μm. The occurrence frequency of the wear debris is much less than other kinds, thus take little effect on wear.

Zonary wear debris is a rare form of artificial joint. It can be divided into three types by its morphology and forming mechanism. The first kind of zonary wear debris is produced for the hard abrasive scraps on soft surface. Clear scraping wrinkle texture can be seen on its surface. The size of wear debris is often over 100 μm, but it is difficult to find. The second kind of zonary wear debris which has a large size and a thin thickness, is produced when tearing wear debris is stretched in the process of friction. The third kind of zonary wear debris is generated by kneading sheet wear debris into rope during the test process (Fig. 5f), showing the combined motion state of artificial joint tribology system.

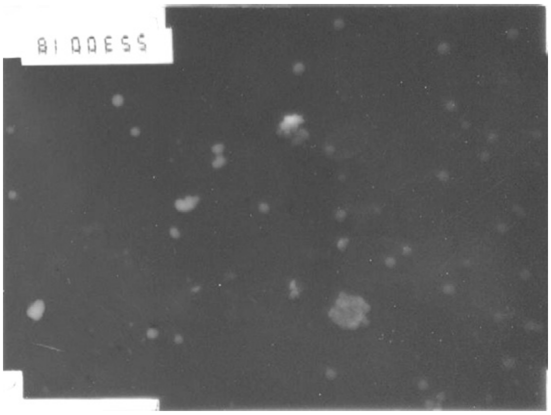

Fig. 6. TEM image (×65k) of UHMWPE wear debris from the implanted artificial joint.

3.2.2. *Morphology of wear debris from the implanted artificial joint*

Fatigue wear is the major wear mode when the artificial joint was implanted into body [13]. The initially produced wear debris exhibits a sheet structure, and this sheet wear debris breaks into some tiny granular debris in the process of movement of friction pairs. Because the wear debris with the spherical structure possesses the lowest energy structure, the wear debris will turn into subsphaeroidal structure if it exists enough time in the lubricant. This point is confirmed by the morphology of the extracted wear debris of the artificial joint. Fig. 6 shows the TEM image of UHMWPE wear debris. It shows that the most wear debris have the spherical or subsphaeroidal shape, and a small amount of the debris has the unbroken plate structure. Fig. 7 shows the typical shape of wear debris of the pathological human joint.

3.2.3. *Comparison between the morphology of two kinds of wear debris*

The results shows that the UHMWPE wear debris obtained from the simulator have the shape of spherical, block, tear, sheet, rod, strip etc. The shape of wear debris is variable, and it gradually turns into spherical or subsphaeroidal with the decrease of the particle diameter. The subsphaeroidal debris takes the most amount of the wear debris, while shares a smaller volume percentage. Moreover, the large wear debris with the shape of sheet or block, takes a small amount and shares a larger volume percentage. On the other hand, wear debris from the implanted artificial joint have a smaller size, mainly consisting of the spherical debris as well as a handful of sheet debris. The morphology of wear debris shows that there

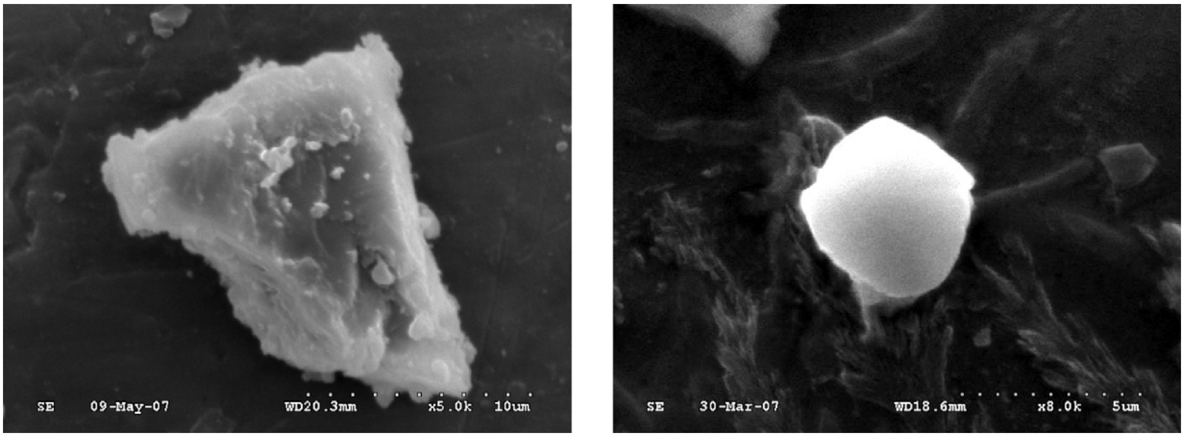
SE 09-May-07 WD20.3mm x5.0k 10um
SE 30-Mar-07 WD18.6mm x8.0k 5um

Fig. 7. Typical morphology of UHMWPE wear debris from the implanted artificial joint.

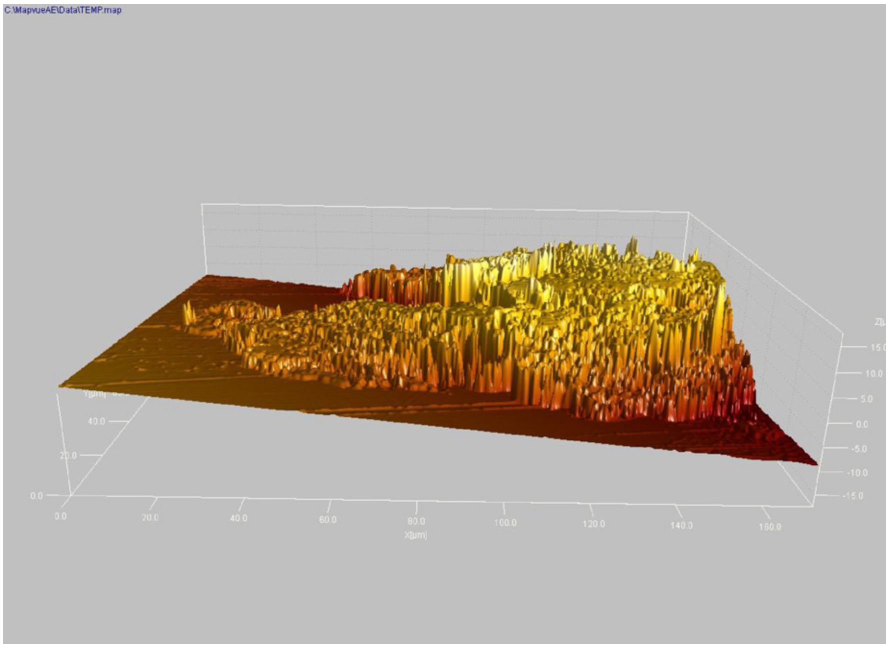

Fig. 8. Three-dimensional morphology and thickness characters of sheet wear debris.

are serious adhesive wear and tear phenomenon besides fatigue wear between the cotyle and articular head of the simulator. Contrastively, wear of the implanted artificial joint is a fatigue wear, producing some sheet wear debris which will be easily broken into spherical and subsphaeroidal debris.

3.3. *Characterization of the three-dimensional morphology and thickness of wear debris*

The three-dimensional morphology and thickness of wear debris are investigated using MiaoXAM2.5X-50X Ultra-precision Contourgraph. The maximum test range in the direction of *Z*-axis (direction of thickness) of the testing instrument is 1 mm, and its precision is 0.1 nm. In order to get accurate data of thickness, the roughness of microslide should be sufficiently low. The result shows that the thickness of UHMWPE wear debris in simulating test, which is basically below 50 µm, has an obvious grading phenomenon [14]. The thickness of spherical and subsphaeroidal wear debris is usually less than 10 µm. The thickness of spherical debris is less than 1 µm and uniform, and its thickness value presents strong stability and grading. Sheet wear debris have a larger thickness of usually between 1 µm and 20 µm and a certain regularity. Fig. 8 shows a three-dimensional morphology and thickness characteristics of sheet wear debris tested using contourgraph. Block wear debris have the thicknest thickness, and the largest in the test is over 70 µm. Its thickness distribution range from 5 µm to 50 µm. The studies on thickness of other wear debris show that strip wear debris and rod debris have thinner thickness. Especially,

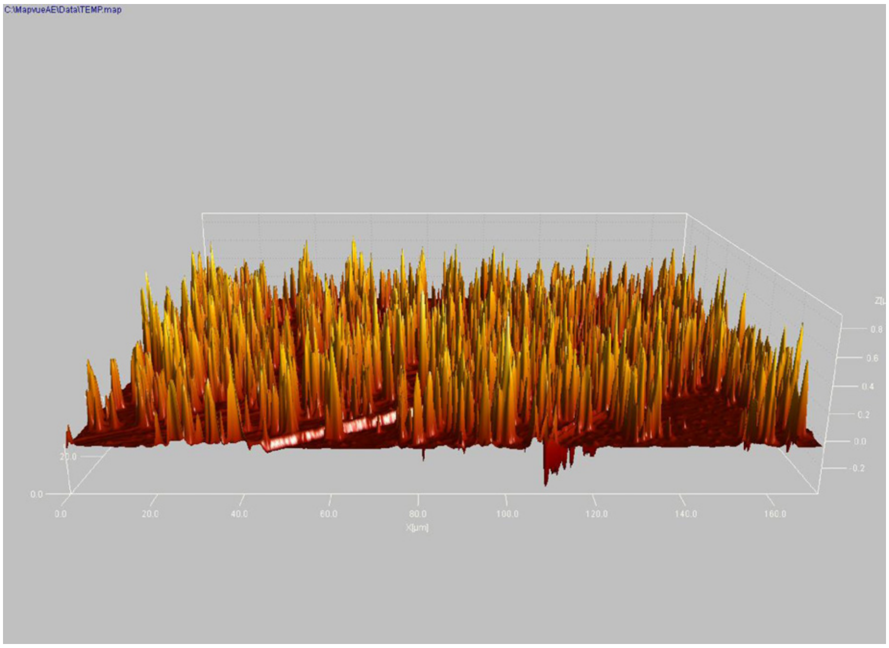

Fig. 9. Three-dimensional morphology and thickness characters of UHMWPE wear debris from the implanted artificial joint.

the thickness of strip wear debris can reach dozens of nanometers.

For wear debris from the implanted artificial joint, its thickness distribution is most below 5 μm except a small amount of debris with a larger size. The thickness of wear debris had a strong uniformity, as shown in Fig. 9.

4. Conclusions

In this paper, the studies of UHMWPE wear debris obtained from implanted artificial joint and hip joint tester are performed by comparing their size distribution, shape, 3-D feature, and thickness. The conclusions are following:

(1) The average diameter of the wear debris from joint simulator is 7.54 μm, and its medium diameter is 6.89 μm. The average diameter of the wear debris from artificial joint is 1.33 μm, is about 18% of the wear debris' from joint simulator, and the medium diameter of 2.95 μm, is about 43% of the wear debris' from joint simulator.

(2) The morphology of wear debris from the implanted artificial joint and hip joint simulator was investigated and discussed. Analysis shows that the UHMWPE wear debris gotten from the simulator have the shape of spherical, block, tear, sheet, rod, strip etc. The shape of wear debris gradually turns into spherical or subsphaeroidal with the decrease of diameter. The subsphaeroidal wear debris takes up the majority of the debris and shares a smaller percentage of the total volume. Moreover, larger wear debris, which basically have the contour of sheet or block, accounts for a small amount of the debris and shares a larger percentage of the total volume. The wear debris from the implanted artificial joint have a smaller size, mainly consisting of spherical wear debris as well as a handful of sheet debris.

(3) The result shows that the thickness distribution of the wear debris from the implanted artificial joint is most below 5 μm and had a strong uniformity; the thickness of UHMWPE wear debris in simulating test, which is basically below 50 μm, has an obvious grading phenomenon.

The wear debris from the artificial joint tester present a different morphology with that from human body, since the morphology of wear debris is an important factor to evaluate artificial joint materials, so we must take the wear debris as one of important parameters for joint simulator design.

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